

# Simulation-Driven ADCS for Sun-Pointing 1U Nano-Satellite: Design and Comprehensive Analysis\*

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**Abstract**— The Sun-pointing attitude mode is essential for Low Earth Orbit (LEO) CubeSats, particularly those relying on solar panels for energy generation. This study presents the development of an Attitude Determination and Control System (ADCS) for the Sun-pointing mode of a 1U nanosatellite, incorporating environment modeling, controller design, and the implementation of a closed-loop output feedback control system within a custom 3D simulation environment. A satellite health monitoring simulator has been created, enabling users to configure various sensor setups, integrate additional sensors seamlessly, and visualize reference, measured, estimated, and controlled states along with pointing error metrics, enhancing performance evaluation and optimization. The ADCS is further validated using STK software, demonstrating precise Sun tracking during orbital operations. Covering the complete process from satellite deployment to mission execution, this study provides a comprehensive framework for understanding and designing satellite attitude control systems, serving as a valuable resource for education, research, and advancing future satellite operational modes by integrating theoretical concepts with practical simulations.

**Keywords**—LEO, ADCS, Sun-pointing, Nanosatellites, and simulation study

## I. INTRODUCTION

The Attitude Determination and Control System (ADCS) is an essential subsystem for satellites, particularly those necessitating precise and stable orientation for their mission goals [1-3]. Following its launch, a satellite undergoes various operational modes in orbit, including detumbling, sun-pointing, and earth nadir-pointing modes, to fulfil its specific requirements. The satellite's sun-pointing mode ensures its solar panels remain orientated towards the sun to optimize solar radiation absorption for battery charging. This sun-pointing mode can also serve as a safe mode when the satellite experiences problems or anomalies and requires restoration of its usual functioning. Researcher have put their efforts to design a ADCS from different angles. Small spacecraft, particularly Nano-satellite as shown in Figure 1.

In the realm of satellite ADCS simulations, the authors of [2] have made significant contributions. They developed an algorithm for attitude determination specifically tailored for 1U nanosatellites operating in a polar Sun-synchronous circular orbit. Their work implements attitude determination using tools such as the IGRF model, J2000 reference frame,

Sun sensor, magnetometer, and gyroscope, with simulations performed in MATLAB. Furthermore, the authors simulated BDOT control algorithms to regulate the satellite's attitude. In [3], the authors successfully assembled, integrated, and tested various phases of the ADCS for the KITSUNE nanosatellite. Complementing these efforts, multiple researchers have conducted simulation-based analytical studies on nanosatellites [4–5]. Hardware-in-the-loop (HIL) and software-in-the-loop (SIL) testing have also been widely employed for ADCS evaluation, leading to diverse proposed solutions [6–8]. The work in [9] focuses on developing attitude determination systems for small-scale satellites, particularly nanosatellites.

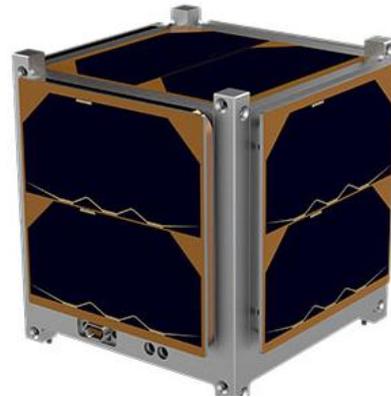


Fig. 1. 1U Nano Satellite (SatCatalog [14])

- Some researchers have adopted a component-level approach to ADCS design [10]. Over the past decade, several small-scale student satellites have been developed [11–12]. However, many of these efforts lack a holistic approach that comprehensively addresses the ADCS design process—from environment modeling to the control law design and its implementation. The literature underscores the need for an integrated methodology in ADCS design that encompasses satellite deployment flow, environment modeling, sensors measurement, attitude determination, and the control law design and its implementation over satellite to actuate it. While [13] presents a notable approach for the nadir-pointing and detumbling modes of a 1U satellite using magnetorquers, it primarily focuses on main control strategies and overlooks aspects such as initial launch conditions and environment modeling. There is a critical need to develop an ADCS design for the Sun-pointing mode of nanosatellites that offers a complete and

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detailed framework. Such a framework is presented here to make the satellite closed-loop control easy to any new satellite control researcher. This framework will allow them to understand the process at system-level. For this purpose, we presenting the following contributions: Creating a thorough attitude determination and control system (ADCS) for the sun-pointing mode of a 1U satellite, covering the complete process from initial environment modeling to control design and its execution over 1U nano satellite. This encompasses the analysis of space environment modelling, the integration of sensor readings for state estimation, the creation of reference generation and error calculation methods, and the application of control laws on a self-constructed 1U satellite body inside a 3D environment.

- Simulating a complete closed-loop controller based on output feedback to implement the control rule, while developing the 1U satellite structure and a 3D orbital model to depict the satellite's trajectory using MATLAB.
- Creating a simulator for satellite health assessment, allowing users to choose the quantity of sensors for sun-pointing mode to conduct comprehensive studies. The simulator enables the assessment of reference, measured, estimated, and controlled states, illustrating the reduction in pointing error as the number of sensors increases.

This study employs sophisticated methodologies to implement, assess, and appraise ADCS designs, enhancing both pedagogical and practical comprehension of satellite control systems.

## II. PROBLEM FORMULATION

The assessment of a satellite's attitude through its sensors, followed by the use of these measurements for control design, constitutes a critical subsystem that stabilizes and regulates the satellite in the harsh conditions of space, located several hundred kilometers from Earth. To define the problem, we must first ascertain the succession of satellite operational modes.

### A. Initial Launching to Space

Upon the deployment of a satellite into space, the kill switch is engaged, thereby activating the Electrical Power System (EPS) of the satellite. The EPS initiates the power distribution to other subsystems for recovery mode, safe mode, attitude log mode, de-tumbling mode, and the sun and earth nadir pointing modes added at the last. The ADCS designed to diminish and regulate the satellite's rotating velocity is referred to as De-tumbling mode. Subsequent to the detumbling mode, the satellite orientates its solar panels towards the sun to meet the electrical power demands of all other subsystems. This configuration is referred to as the Sun Pointing Modes.

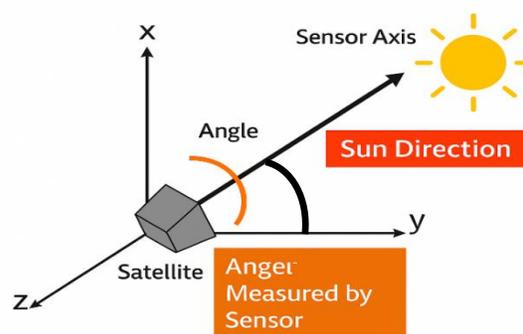


Fig. 2. The angle between each sun sensor's axis and the sun's direction yields a cosine-based measurement, collectively used to estimate the sun vector in the body frame.

### B. Environmental Modelling for Sun-pointing Mode

To ascertain the satellite's attitude, we must first delineate the spatial environment, namely the orbital period, which is 94 minutes for the orbit height of 525km. Subsequently, we established the sensor's configuration (optical payload) and the satellite's rotating model. The eclipse phase, wherein the Earth is positioned between the satellite and the Sun, is estimated to last 32 minutes for a complete orbit, or 34 percent of the total duration.

### Sun-pointing Mode

Figure 2 illustrates the satellite sun pointing mode, depicting a satellite in orbit around the Earth, with the sun represented by a larger circle. The red arrow indicates the true direction of the sun, whereas the blue vector represents the measured direction of the sun as determined by the satellite's current orientation. The ADCS is tasked with adjusting the solar panel orientation towards the sun for optimal electrical power generation.

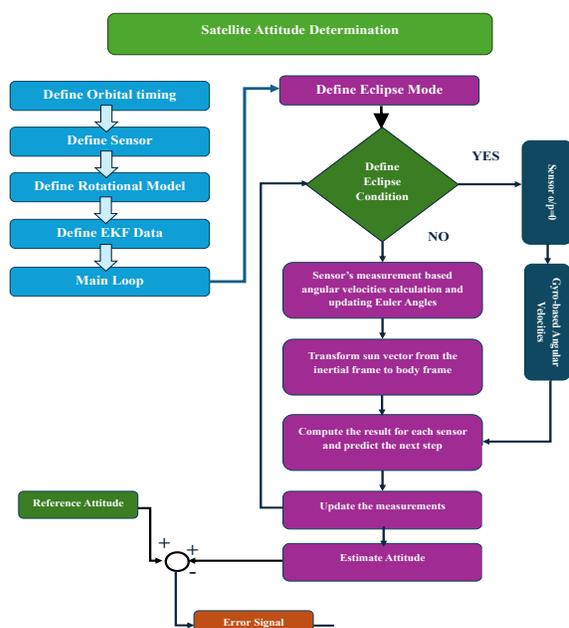


Fig. 3. System-level flowchart of the satellite attitude determination process, including initialization, sensor input handling, eclipse detection, and real-time attitude estimation using an Extended Kalman Filter.

### A. Attitude Determination

The satellite's attitude determination system uses four sun sensors and a three-axis gyroscope to estimate orientation. The sun sensors, mounted in known body-frame orientations, provide cosine-based scalar measurements of the sun's direction, with zero output during eclipse. The gyroscope measures body-frame angular velocities (roll, pitch, yaw). An Extended Kalman Filter (EKF) fuses sun sensor data in Cartesian coordinates to estimate the sun vector in the body frame, which is then transformed to the LVLH and inertial frames. A reference direction from OBC-based orbital data is used to compute the attitude error for control. The full estimation and control architecture is shown in Fig. 3.

### III. OUTPUT FEEDBACK-BASED CONTROL DESIGN

To control the satellite operation in the sun pointing mode, output feedback-based proportional integral and derivative (PID) control law is used as it requires only measured output for control and doesn't need any system state (states are rarely available). The PID controller is used due to its tuning ability and easy design and implementation. The input to the controller is an error between orientation in the planned mission and Kalman filter-based estimated sun direction as demonstrated in Figure 4. For reference direction in our case, we used a 3D unit vector in the cartesian coordinates. The inner loop of the figure is for the detumbling stage when we reduce the satellite angular velocities after launch.

$$Output_e = K_p \cdot e[k] + K_i \cdot \sum_{j=0}^k e[j] \cdot T + K_d \cdot \frac{e[k] - e[k-1]}{T} \quad (1)$$

### IV. RESULTS & DISCUSSIONS

A simulator for satellite health monitoring is constructed

using MATLAB when the designed control is implemented

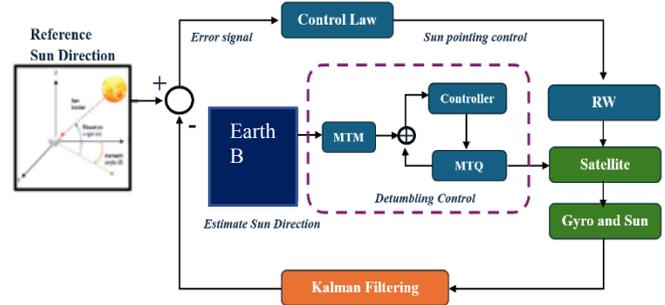


Fig. 4. Block diagram of the output feedback-based closed-loop control system for sun-pointing, incorporating Kalman filtering, sensor fusion, and actuator control.

in the satellite system. The simulator features a graphical user interface enabling users to observe sensor statuses via several subplots. Users can choose the quantity of sun sensors for sun-pointing operations. The subplots illustrate the conditions of active sun sensors, reference sun states, measured states, estimated states, and controlled states.

The output from the satellite sensors, which indicates the sun's direction, is expressed as voltage amplitudes. Elevated voltage is recorded when a sun sensor is orientated towards the sun, however no voltage is generated during eclipse mode, allowing the controller to further optimize time slots and voltage values, hence minimizing pointing errors to millivolt levels, as depicted in Figure 7. A 3D environment and a 1U satellite model were developed in MATLAB to orient the satellite towards the reference solar direction, with the spacecraft depicted in blue. The sun's direction was represented using vectors: the reference sun direction in the inertial reference frame and the body frame, depicted as red vectors; the estimated sun direction as a blue vector; and the controlled sun direction as a green vector being maneuvered in accordance with the reference and controlled vector

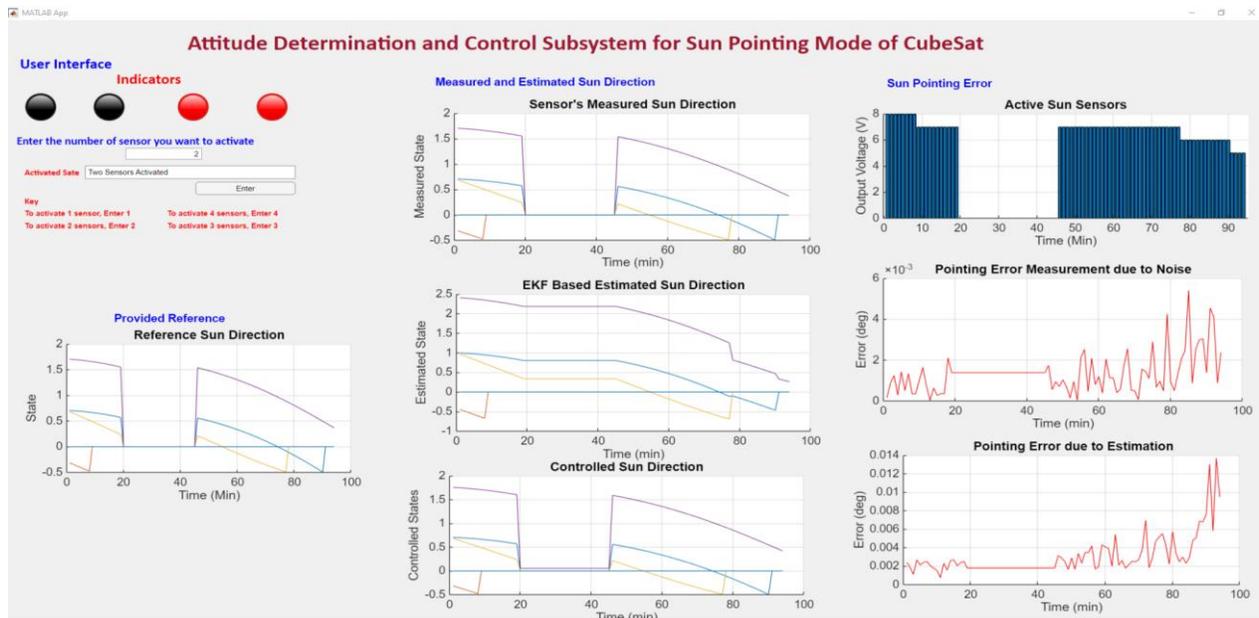


Fig. 5. MATLAB interface for CubeSat sun-pointing ADCS showing EKF-based estimation, control states, sensor activity, and pointing error relative to a reference sun vector.

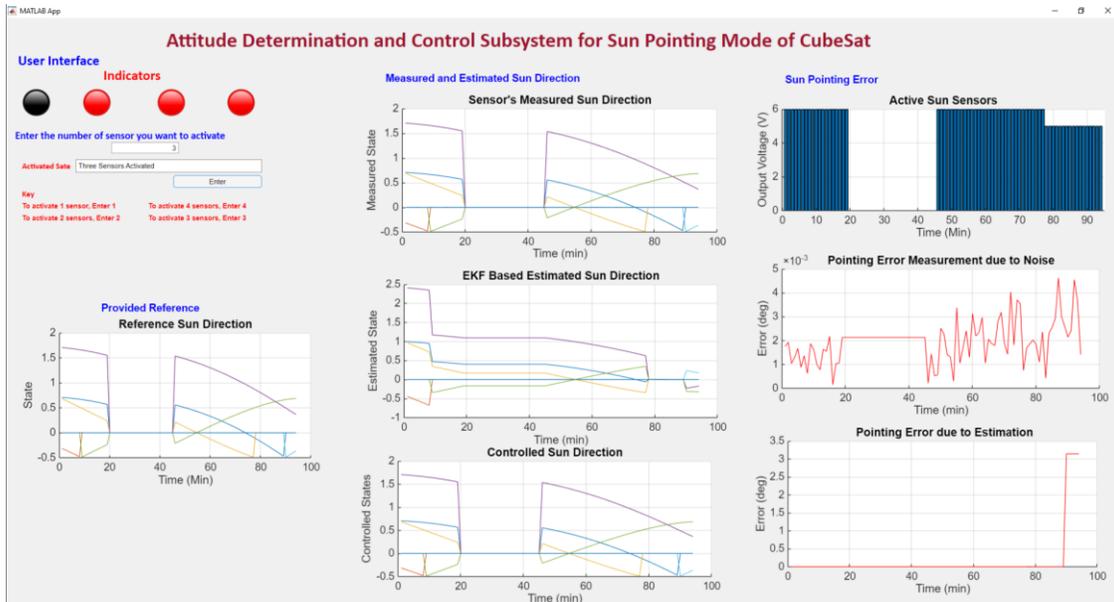


Fig. 6. Reference, Measured, Estimated and Controlled States with three sun sensors

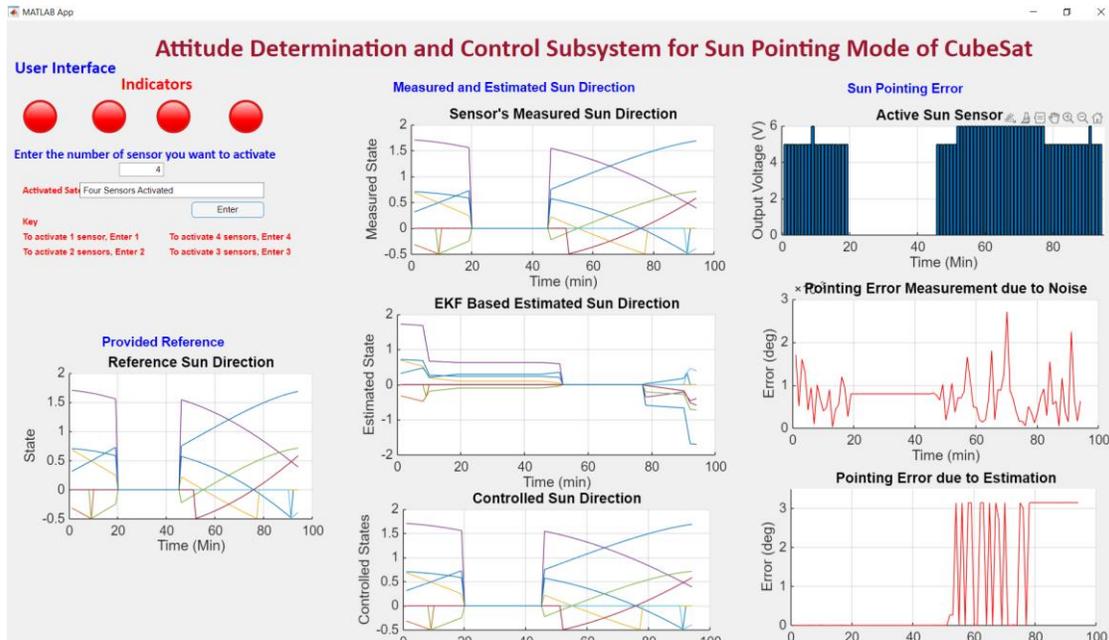


Fig. 7. Reference, Measured, Estimated and Controlled States with four sun sensors

The 3D depiction in Figure 7 illustrates the satellite

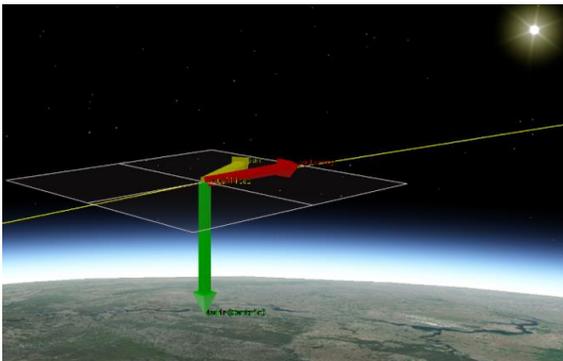


Fig. 8. Sun Pointing Mode validation using STK, Yellow vector is towards the sun

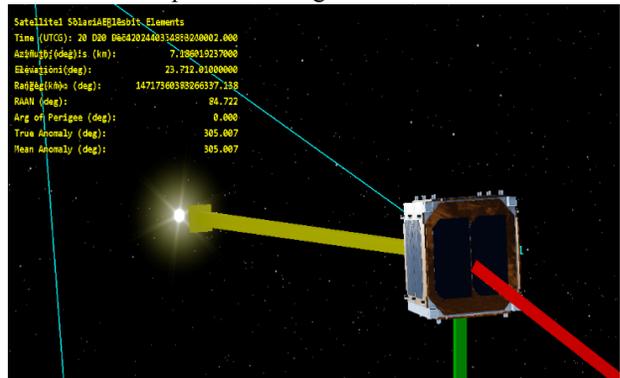


Fig. 9. Sun Pointing Mode Satellite view

Figure 8 further demonstrates the effective alignment and actuation of the satellite in the intended orientation. This method underscores the efficacy of the control system in executing accurate sun-pointing actions. Figure 10 and figure 11 shows clearly the actuation of controlled movement of 1U satellite for sun direction. Figure 8 and figure 9 clearly demonstrate the sun pointing mode of the 1U satellite, where the yellow vector is for the sun direction. The red color vector is for velocity direction and the green vector is towards the earth nadir direction. Figure 12 is included to illustrate the satellite's primary operational modes and their transitions throughout the mission timeline.

## V. CONCLUSION & FUTURE RECOMMENDATIONS

Within the scope of this work, the comprehensive design of an Attitude Determination and Control System for the sun-pointing mode of a 1U satellite is presented. This design encompasses the entire process, beginning with the first launch and continuing through the control design and implementation of control laws. With the help of MATLAB, an output feedback-based controller is successfully simulated in a three-dimensional environment that was developed specifically for it. In addition, a specialized simulator for satellite health monitoring is being built. This simulator gives users the ability to choose the number of sensors for sun-pointing operations in order to carry out in-depth analysis. The controller's performance and accuracy are validated by the subplots of the simulator, which show that there is a significant reduction in aiming error as the number of sensors grows. This entire closed-loop ADCS design not only

provides insights into satellite operation modes but also acts as a significant instructional tool, encouraging a deeper understanding of satellite control systems and their practical application for various academic and research reasons. It is possible that in subsequent work, numerous improvements to the current architecture of the ADCS for the sun-pointing mode will be investigated. The incorporation of sophisticated sensor fusion methods, such as Kalman or particle filters, has the potential to enhance the precision of state estimates,

particularly in situations that are dynamic or noisy. In order to improve the precision of the control, it might be possible to study the possibility of including other actuation systems such as reaction wheels or micro-thrusters. It is also possible to bridge the gap between simulation and real-world implementation by extending the capability of the simulator to provide a more robust validation framework. It is possible that future research will also incorporate AI-driven adaptive control approaches, include hardware-in-the-loop (HIL) testing. These techniques will allow for the dynamic adjustment of controller parameters in response to changes in the environment and operations, thereby ensuring optimal performance in a variety of scenarios. These developments have the potential to considerably improve the adaptability and dependability of ADCS designs for small-scale satellites, hence clearing the way for more widespread applications in the fields of education and research.

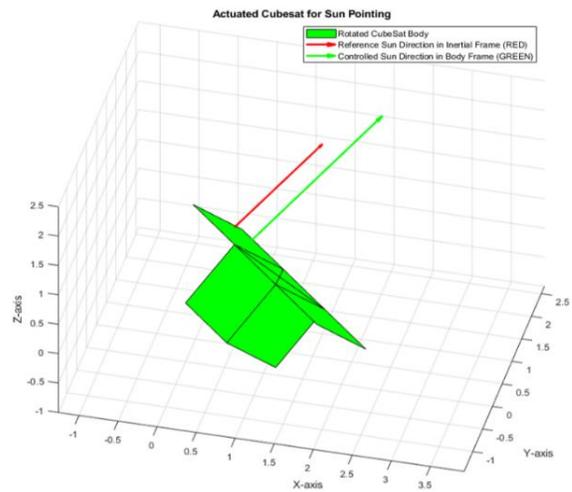


Fig. 10. Actuated CubeSat in the controlled sun direction vector

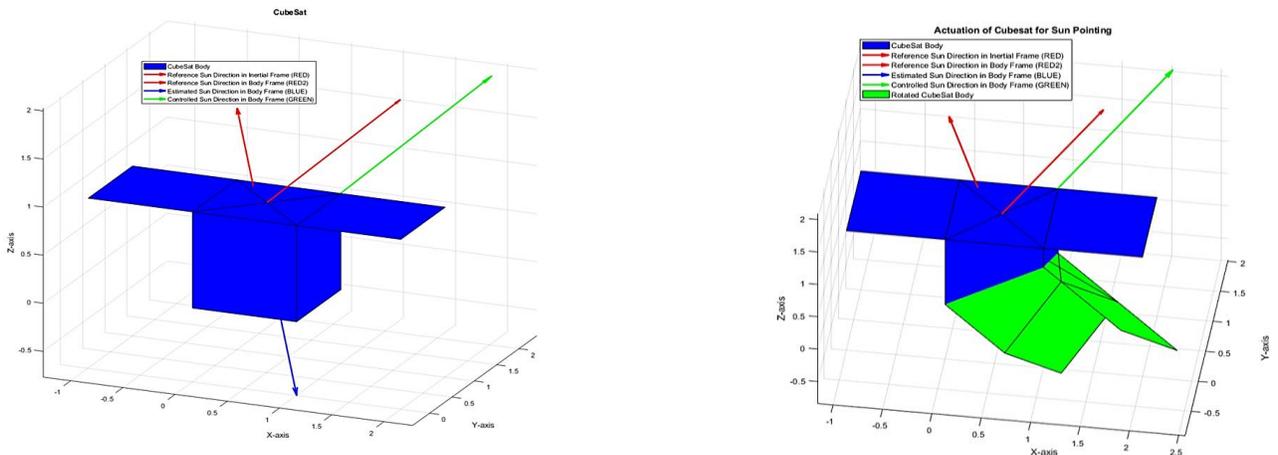


Fig. 11. Controlled Actuation of 1U CubeSat (Actuation of Satellite is demonstrated using MATLAB APP Designer)

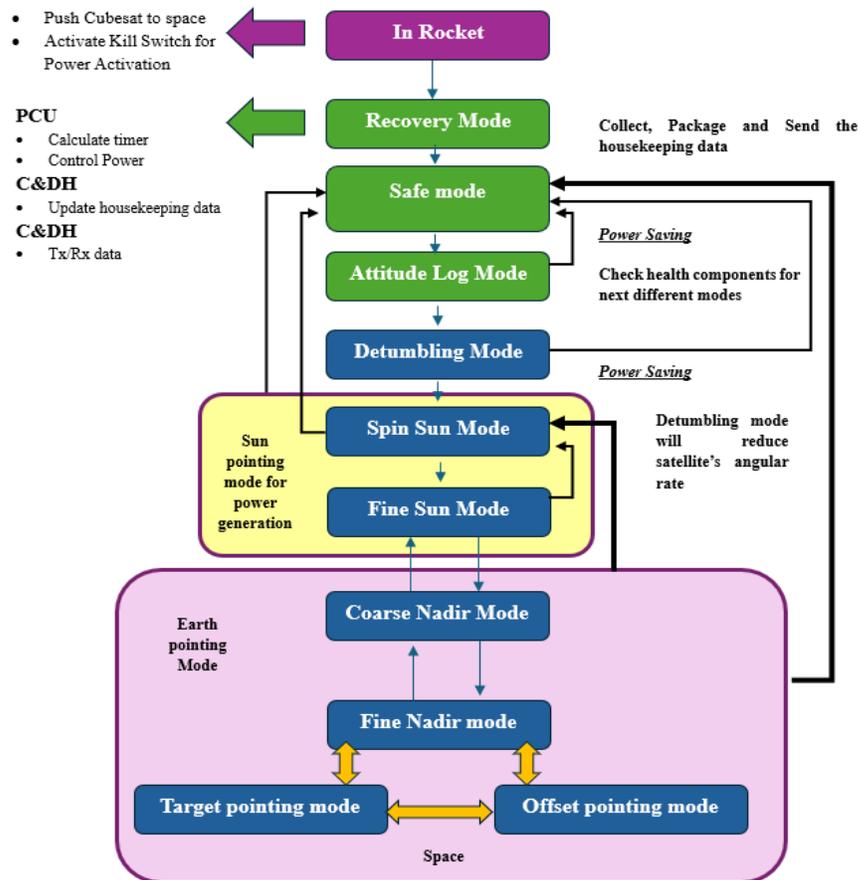


Fig. 12. CubeSat mission mode flowchart illustrating transitions from launch to recovery, detumbling, sun-pointing, and Earth-pointing modes, each designed for power generation, attitude stabilization, and mission-specific pointing tasks.

## VI. ACKNOWLEDGMENT

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